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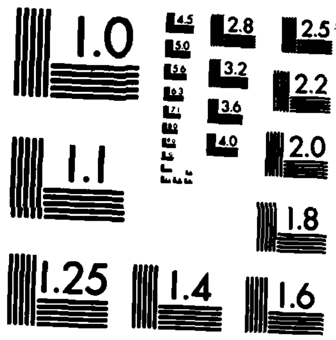
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FINAL REPORT

ONR Grant N00014-76-C-037

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CONTENTS

1. Summary of Research

The general areas of research studied under this grant have dealt with the mechanisms for the generation of wave noise in connection with auroral precipitation. The largest effort has been devoted to understanding the generation of wave noise called VLF hiss. VLF hiss is radio noise in the whistler mode associated with auroral arcs. We have tried to understand the generation of this noise by the auroral electron beam and the subsequent interaction of this noise back on the auroral electrons. The major research accomplishment achieved under this grant is the development of a complete and detailed theoretical model that successfully predicts the power flux spectra of whistler noise generated by a given auroral electron beam. In addition, wave noise in other modes such as electromagnetic AKR are also generated by the auroral electron beam. These phenomena have also been investigated in the context of the theoretical model developed to study VLF hiss. Furthermore, the study of wave phenomena connected with the aurora has not been restricted solely to the ionosphere. The generation of low frequency turbulence in the magnetotail has also been examined. In the following, the details of the research conducted in each of these areas is given along with results and conclusions.

1.1 Plasma dynamics of the auroral electron beam

1.1.1 Generation of Electrostatic Noise-Linear Growth

A variety of radio noise emissions are associated with auroral arcs. Most prominent among them in terms of radiated power and frequency of occurrence are VLF hiss and auroral kilometric radiation (AKR). Auroral hiss was originally thought to arise from incoherent Cerenkov radiation[1] but there were indications that observed power levels could not be produced by this mechanism.[2] Early research

conducted under this grant led Maggs[3] to suggest that VLF hiss was produced by an instability associated with the auroral electron beam. This mechanism was first reported to the community in December 1974 at the Fall AGU meeting in San Francisco. A great deal of research which refined and improved this original work was subsequently conducted under this grant. The final result is a detailed theoretical model for the generation of electrostatic noise by the auroral electron beam which agrees very well with observation.

The basic idea is that VLF hiss is generated in the whistler mode but at propagation angles very near the resonance cone angle where the wave is nearly purely electrostatic. Under these circumstances the whistler couples to the electron beam through the Landau resonance. The waves grow because the electron distribution has a region of positive slope created by the precipitating auroral electrons in the 1-10 keV range. The initial theory hypothesized the existence of this positive slope region. Subsequent satellite observations have confirmed that the positive slope region is a very common feature of the auroral electron distribution.

The Landau resonant instability that was suggested as the source for VLF hiss is a convective instability. Quantitative estimates of the power flux levels of VLF hiss were obtained by numerically integrating the wave kinetic equation along ray paths using a model auroral arc and ionosphere. Results of these calculations were reported in the benchmark paper, 'Coherent Generation of VLF Hiss'.[4]

A feature of the initial calculation was that it predicted very high power levels near the electron plasma frequency in regions of the ionsophere where this frequency was smaller than the electron gyrofrequency. The reasons for this were twofold. Firts, a linear growth rate had been assumed for wave amplification and nonlinear modifications of the wave spectrum and electron

distribution were ignored. Second, the effects of wave refraction due to ionospheric density gradients in the magnetic meridian plane were not considered. Investigation of this latter process revealed a dramatic effect on the wave power spectrum because wave noise propagating at frequencies near the electron plasma frequency are quickly refracted out of the spatially limited beam region. Power levels near the plasma frequency are limited to reasonable levels even assuming a linear growth rate. Calculations of electrostatic noise power flux levels using a model ionosphere with density gradients in the magnetic meridian plane were presented in the paper: 'Electrostatic Noise Generated by the Auroral Electron Beam'.[5] Noise levels in both the whistler and upper hybrid bands were calculated and it was found that power levels in the whistler band should be much larger than those in the upper hybrid band except at low altitudes ($\lesssim$ 500 km).

Up to this point calculations of wave power flux spectra had been carried out without including the population of electrons observed in measured auroral electron precipitation to follow a roughly power law distribution in the energy range of a few electron volts to just below the beam energy. These particles contribute significantly to cyclotron damping especially in regions of the ionosphere where the electron plasma frequency is comparable to the electron gyrofrequency and especially for waves propagating in the upper hybrid band. These particles were included in calculations of the power flux spectrum and the results reported in: 'Damping of Electrostatic Noise by Warm Auroral Electrons'.[6]

At this point a refined theoretical model of wave growth on a model auroral beam had been developed but was restricted in applicability because the model beam was assumed to be a drifting Maxwellian. While the actual distribution and production mechanism of the auroral beam is not known a drifting Maxwellian would change in the geophysical environment because of the changing magnetic

field strength. To account for this effect the model was improved by incorporating a model beam with a changing pitch angle distribution. The model beam evolved from an initially drifting Maxwellian distribution at altitudes near the source to one with positive slope at nearly all down-coming pitch angles. The evolution of the distribution was calculated assuming conservation of total kinetic energy and first adiabatic invariant. Such a model distribution is consistent with rocket and satellite observations. This refinement was included in the model and reported in two companion papers: 'Altitude Dependent Model of the Auroral Beam and Beam Generated Electrostatic Noise',[7] and 'Amplification of Electrostatic Noise in Cyclotron Resonance with an Adiabatic Auroral Beam'.[8] At this point a good model of the altitude dependence of linearly grown electrostatic noise had been obtained and the effects of the beam generated noise back on the beam particles could be calculated.

1.1.2 Weak Turbulence of Auroral Beam Dynamics

The calculation of p[illegible] flux spectra is performed by integrating the wave kinetic equation. This equation is derived under assumptions of clearly wave-like properties in the noise constituting the wave spectra. That is, the concepts of wave number, fixed frequency and well defined ray path are employed. These assumptions are consistent only in the weak turbulence environment. The companion weak turbulence process in the particle evolution is quasilinear diffusion. This weak turbulence process alters the particle distribution on time scales, or length scales, long in comparison to the linear growth time or distance.

A study of the height evolution of the auroral beam was carried out assuming that the auroral electron distribution was subject to the process of quasilinear diffusion. A computer code was developed based upon the refined model of linearly grown wave noise. A model was adopted in which the auroral beam originated

at some given height along the auroral field lines as a drifting Maxwellian. The beam distribution then evolves not just due to changing magnetic field strength but due to quasilinear diffusion processes as well.

The calculation is performed by stepping along the field lines in fixed increments. At each point along the field line the power flux is calculated by using an algorithm which averages the growth along ray paths. The spatial derivatives of the beam energy and temperature arising from quasilinear diffusion are then calculated and used to obtain the beam distribution at the next point along the field line. The calculation is then repeated. In this manner the power flux spectra and beam distribution can be found as functions of distance from the source.

Quasilinear diffusion increases the beam temperature and hence limits wave growth. However the beam density tends to increase as the beam travels towards the atmosphere because of the narrowing flux tube cross section. This density increase causes in increase in the growth rate. It is found that the two affects of beam density increase and beam temperature increase tend to balance one another so that under weakly turbulent processes the beam evolves on a scale length comparable to the magnetic field scale length. Amplitudes of wave power flux are limited by this process and tend to peak in the region between 3,000-5,000 km altitude where they can reach flux densities as high as 10^{-9}W/m^2-Hz. The validity of the weak turbulence theory is limited to power levels below those in which the wave energy density is comparable to the plasma energy density.

The incorporation of a detailed beam and ionospheric model together with quasilinear diffusion allows for a very sophisticated predictive model for the auroral beam and beam produced noise. The application of this model to an analysis of observed auroral zone data should lead to a good understanding of the important plasma processes involved. This detailed quantitative model

is the result of years of research and is reported in preliminary form in 'Interaction Between Natural Particle Beams and Space Plasmas'[9] while the final results are reported in 'Weak Turbulence Theory of Auroral Beam Dynamics'.[10]

1.1.3 Strongly Turbulent Process in Naturally Occurring Beam-Plasma Systems

For situations in which large amplitudes of electrostatic noise are generated the dynamics of the plasma are greatly affected by the presence of the waves and nonlinear processes can be of primary importance in determining the wave and plasma behavior. Amplitudes of auroral beam produced noise can be large enough that nonlinear processes are dominant. In such a case the ion dynamics are modified by the presence of the waves through the ponderomotive force. For electrostatic waves propagating at the resonance cone angle the ponderomotive force can leaa to self-focusing and formation of cavitons. Cavitons are nonlinearly formed density cavities in which trapped high frequency wave pressure plays a major role in the plasma dynamics. The trapped high frequency electrostatic noise can in turn interact with the step gradients of the density cavity and lead to electromagnetic radiation. Such a process could be a candidate for the source of auroral kilometric radiation. This process has been investigated and it was found that, for cases in which the plasma density in auroral arcs is large enough that the second harmonic of the electron plasma frequency is above the right hand cut-off, observed AKR power levels could be produced by this process. These results were reported in 'Theory of Electromagnetic Waves on Auroral Field Lines'.[11]

Observations of beam produced turbulence near the vicinity of Jupiter's bow shock indicated that caviton formation by self-focusing of electrostatic plasma oscillations may occur. This data was investigated in detail to determine if indeed caviton formation was occuring. It was concluded that the actual

dominant process was multiple scattering of beam plasmons off a background of ion acoustic turbulence already present in the ambient plasma. These results were reported in 'Parametric Scattering and Spatial Collapse of Beam Driven Langmuir Waves in the Solar Wind'.[12]

1.2 Low Frequency Turbulence in the Magnetotail

The auroral zones map along magnetic field lines into the plasma sheet-neutral sheet region of the magnetotail. This region has been observed to be a source of large amplitude low frequency magnetic turbulence. This turbulence is important in the bulk flow dynamics of the plasma in this region and therefore is important in determining the input parameters of the auroral beam formation region.

As plasma flows in towards the earth from the outer magnetospheric tail regions the pitch angle distribution becomes field aligned because of relatively constant equatorial magnetic field strength but decreasing field line length. The field aligned distribution results as a consequence of conservation of the first and second adiabatic invariants of the particles. Such a field aligned distribution can be unstable to firehose-type instabilities.

Because of the long wavelengths of low frequency turbulence the analysis of this problem requires a nonlocal treatment. The complicated magnetic geometry also adds to the difficulties. An analysis of the onset of low frequency turbulence in a magnetotail-like magnetic geometry was carried out using a variational analysis. A technique was developed in which the eigenfunctions of this non-self-adjount problem could be found and a variational principle was develped to analyze the plasma stability. It was found that magnetic turbulence first occured in the region of the tail in which magnetic tension was no longer accelerating plasma inwards. The onset of turbulence greatly relieved the decelerating tension

of the plasma, however, by keeping the parallel and perpendicular temperature ratio near the force free value. Thus low frequency turbulence plays an important role in allowing deep penetration of the plasma into the inner magnetosphere from the tail region. These results were reported in 'The Firehose Instability in a Magnetotail Geometry'.[13]

1.3 Magnetospheric Radio Bursts

Electromagnetic radiation similar to AKR emissions observed in the Earth's magnetosphere have been discovered to emanate from both Jupiter and Saturn. Speculating that these bursts of electromagnetic radiation may be produced by any magnetized rotating body immersed in a plasma flow, the characteristic burst spectrums from the three planets: Earth, Jupiter and Saturn were scaled to planetary magnetic field strengths and field line reconnection rates. Using the patterns emerging from the scaled data, characteristics of possible magnetospheric radio bursts from Uranus and Neptune were predicted. Results were reported in 'On the Possibility of Detecting Magnetospheric Radio Bursts from Uranus and Neptune'.[14]

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2. Taylor, W.W.L. and S.D. Shawhan, 'A Test of Incoherent Cerenkov Radiation for VLF Hiss and Other Magnetospheric Emissions', J. Geophys. Res., 79, 105-117, 1974.
3. Maggs, J.E., 'Coherent Generation of VLF Hiss', paper SM-93 given at Fal Meeting of the American Geophysical Union, San Francisco, CA, 1974.
4. Maggs, J.E., 'Coherent Generation of VLF Hiss', J. Geophys. Res., 81, 1707-1724, 1976.
5. Maggs, J.E., 'Electrostatic Noise Generated by the Auroral Electron Beam', J. Geophys. Res., 83, 3173-3187, 1978.
6. Lotko, W. and J.E. Maggs, 'Damping of Electrostatic Noise by Warm Auroral Electrons', Planet. Space Sci., 27, 1491-1506, 1979.
7. Maggs, J.E. and W. Lotko, 'Altitude Dependent Model of the Auroral Beam and Beam Generated Electrostatic Noise', J. Geophys. Res., 86, 3439-3448, 1981.
8. Lotko, W. and J.E. Maggs, 'Amplification of Electrostatic Noise in Cyclotron Resonance with an Adiabatic Auroral Beam', J. Geophys. Res., 86, 3449-3458, 1981.
9. Maggs, J.E., 'Interaction Between Natural Particle Beams and Space Plasmas', in Artificial Particle Beams in Space Plasma Studies, edited by B. Grandal, Plenum Press, 1982.
10. Maggs, J.E., 'Weak Turbulence Theory of Auroral Beam Dynamics', in preparation, 1983.
11. Maggs, J.E., 'Theory of Electromagnetic Waves on Auroral Field Lines', J. Geomag. Geoelectr., 30, 273-287, 1978.

12. Gurnett, D.A., J.E. Maggs, D.L. Gallagher, W.S. Kurth, and F.L. Scarf, 'Parametric Scattering and Spatial Collapse of Beam Driven Langmuir Waves in the Solar Wind', J. Geophys. Res., 86, 8833-8841, 1981.

13. Maggs, J.E., 'The Firehose Instability in a Magnetotail Geometry', Ctr. for Plasma Phys. and Fusion Eng., UCLA, PPG-497, June 1980.

14. Kennel, C.F. and J.E. Maggs, 'On the Possibility of Detecting Magnetospheric Radio Bursts from Uranus and Neptune', Nature, 267, 299, 1976.

2. Publications

The following is a list of the papers and articles resulting from research conducted under ONR Grant N00014-76-C-037.

Maggs, J.E., Coherent Generation of VLF Hiss, J. Geophys. Res., 81, 1707-1724, 1976.

Kennel, C.F. and J.E. Maggs, On the Possibility of Detecting Magnetospheric Radio Bursts from Uranus and Neptune, Nature, 267, 299, 1976.

Maggs, J.E., Electrostatic Noise Generated by the Auroral Electron Beam, J. Geophys. Res., 83, 3173-3187, 1978.

Maggs, J.E., Theory of Electromagnetic Waves on Auroral Field Lines, J. Geomag. Geoelectr., 30, 273-287, 1978.

Lotko, W. and J.E. Maggs, Damping of Electrostatic Noise by Warm Auroral Electrons, Planet. Space Sci., 27, 1491-1506, 1979.

Maggs, J.E., The Firehose Instability in a Magnetotail Geometry, Center for Plasma Physics and Fusion Engineering, UCLA, PPG-497, June, 1980.

Maggs, J.E. and W. Lotko, Altitude Dependent Model of the Auroral Beam and Beam Generated Electrostatic Noise, J. Geophys. Res., 86, 3439-3448, 1981.

Lotko, W. and J.E. Maggs, Amplification of Electrostatic Noise in Cyclotron Resonance with an Adiabatic Auroral Beam, J. Geophys. Res., 86, 3449-3458, 1981.

Gurnett, D.A., J.E. Maggs, D.L. Gallagher, W.S. Kurth, and F.L. Scarf, Parametric Scattering and Spatial Collapse of Beam Driven Langmuir Waves in the Solar Wind, J. Geophys. Res., 86, September, 1981.

Maggs, J.E., Altitude Dependence of Auroral Beam Generated Electrostatic Noise, Physics of Auroral Arc Formation, S.I. Akasofu and J.R. Kan, Editors, Geophysical Monograph 25, Am. Geophys. Union, Washington, D.C., 1981.

Maggs, J.E., Interaction Between Natural Particle Beams and Space Plasmas, in Artificial Particle Beams in Space Plasma Studies, B. Grandal, Editor, Plenum Press, New York, 1982.

2.1 Oral Presentations

The following is a list of papers read before professional meetings and colloquia presented to professional groups concerning research performed under ONR Grant N00014-76-C-037.

2.1.1 Contributed Papers:

Coherent Generation of VLF Hiss, SM-93, Fall AGU Meeting, San Francisco, CA, 1974.

The Firehose Instability in the Earth's Magnetotail, SM-35, Fall AGU Meeting, San Francisco, CA, 1975.

Implications of Coherent Generation of VLF Hiss for the Auroral Electron Beam, Active Experiments in Space Plasmas Symposium on Solar Terrestrial Physics, Boulder, Colo., June, 1976.

Damping of Electrostatic Noise by Secondary Auroral Electrons, with W. Lotko, Am. Geophys. Union, Fall Meeting, 1978.

Altitudinal Dependence of Electrostatic Noise Generated by the Auroral Beam, with W. Lotko, Am. Geophys. Union, Fall Meeting, 1979.

2.1.2 Invited Papers:

Coherent Generation of VLF Hiss, SM-18, AGU Meeting, San Francisco, CA, 1975.

Theory of Electromagnetic Waves on Auroral Field Lines, GA 525, IAGA Meeting, Seattle, WA, 1977.

Plasma Processes in Auroral Arcs, E.G.S. Meeting, Strausbourg, France, August, 1978.

Altitude Dependence of Auroral Beam Generated Electrostatic Noise, AGU Chapman Conference on "Formation of Auroral Arcs", Fairbanks, Alaska, July 1980.

Interaction Between Natural Particle Beams and Space Plasmas, NATO Advanced Research Institute on "Artificial Particle Beams Utilized in Space Plasma Physics" Gielo, Norway, April, 1981.

2.1.3 Colloquia:

Space Science Laboratory, Berkeley, California, March, 1975.

Aerospace Corporation, El Segundo, California, January, 1976.

University of Alberta, Edmonton, Canada, March 1977.

Mullard Space Science Laboratory, Holmbury St. Mary, U.K., July, 1978.

Marshall Space Flight Center, Huntsville, Alabama, June, 1981.

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